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From a conservation trap to a conservation solution: lessons from intensively managed Montagu's harriers in Catalonia

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Abstract

Many threatened species are conserved and managed following conservation programs. These conservation programs are usually developed by intuition without assessing their biological and long-term economic sustainability. As a result, many of these programs may operate more as conservation traps rather than as conservation solutions. The current conservation program of Montagu`s harrier (*Circus pygargus*), a ground-nesting bird of prey, in Catalonia (NE Spain) aims to protect nests located in farmlands by delaying the harvest around the nest and compensating farmers for the economic loss associated to this measure. However, this conservation program has been flagged as a conservation trap due to the fact that its costs have been increasing over time, possibly compromising its long-term maintainability, but may need to be maintained indefinitely to have a long-term impact on the population; thus, the viability of the species is largely dependent on the duration of monetary incentives, which may be compromised. In the present work, population viability analyses were used in order to find a conservation management scenario that decreases the risk of a conservation trap, or at least minimizes the medium-term expenditure on conservation, considering simultaneously natural vegetation and agricultural breeding populations of Montagu's harrier in Catalonia. The results hereby presented demonstrate that if the conservation goal is to maintain a self-sustainable population, it might be possible to avoid the conservation trap by increasing the population size of the natural vegetation breeding populations. However, if the conservation goal is to maintain also the agricultural breeding population, it would be impossible to fully avoid a conservation trap. Different management scenarios that might minimize the medium-term expenditure of scarce conservation funds are presented. The results obtained suggest that selecting a conservation program based only on biological or cost-effective targets might result in a conservation trap.

Key words: *Circus pygargus, population viability analysis, conservation programs, conservation goal, cost-effectiveness.*

Résumé

De nombreuses espèces menacées sont conservées et gérées suite aux programmes de conservation. Ces programmes de conservation sont généralement développés par intuition sans évaluer leur viabilité biologique et économique à long terme. En conséquence, plusieurs de ces programmes peuvent fonctionner comme des pièges de conservation plutôt que comme des solutions de conservation. Le programme actuel de conservation du busard cendré (*Circus pygargus*), une rapace nichant au sol, en Catalogne (NE Espagne), vise à protéger les nids situés dans les terres agricoles en retardant la récolte autour du nid, moyennant une indemnisation aux agriculteurs pour les pertes économiques. Cependant, ce programme de conservation a été marquée comme un piège de conservation en raison du fait que ses coûts ont augmenté au fil du temps, ce qui peut compromettre sa maintenance à long terme, mais doit être maintenu dans le temps pour avoir un effet a long-terme dans la population; donc, la viabilité de l´espèce peut être dépendant de la durabilité des budgets pour sa conservation. Dans le projet actuel, des analyses de viabilité de la population ont été utilisés afin de trouver un scénario de gestion de la conservation qui diminue le risque d'un piège de conservation, ou au moins de minimiser les dépenses à moyen terme, en tenant compte simultanément les populations reproductrices dans végétation naturelle et agricole du busard cendré dans Catalogne. Les résultats démontrent que si l'objectif de conservation est de maintenir une population autosuffisante au niveau régional, il pourrait être possible d'éviter le piège de la conservation en augmentant la taille des populations reproductrices en végétation naturelle. Toutefois, si l'objectif de conservation est aussi de maintenir les populations reproductrices agricoles, il serait impossible d'éviter totalement un piège de conservation. Différents scénarios de gestion qui pourraient réduire les dépenses des fonds de conservation à moyen terme sont présentés. Les résultats obtenus montrent que la sélection d'un programme de conservation basée uniquement sur des cibles biologiques ou économiquement rentables pourrait entraîner dans un piège de la conservation.

Introduction

Globally, the species' extinction rate has increased about 1000 times from the background rate of extinction over the last centuries due to human activities (Pimm *et al*. 2014). This extinction rate is so high that it is considered as the sixth mass extinction event in the world's history (Thomas *et al.* 2003). Additionally to these extinction events, a progressing defaunation is occurring across the globe, with significant impacts on local community dynamics and ecosystems' functions and services (Dirzo *et al.* 2014). To overcome this biological crisis, massive-scale conservation efforts are needed, but economic resources are limited and insufficient to protect all threatened or vulnerable species and ecosystems (McCarthy *et al.* 2012). Therefore, hard choices are to be made as for what, where and how to protect in order to minimize the misallocation of scarce resources and maximize the benefits (Botrill *et al.* 2008).

Traditionally, many such targeted conservation efforts have been developed opportunistically based on experts' previous experiences and intuition instead of sound scientific evidence (Duke *et al*. 2013; Sutherland *et al*. 2004). When such evidence is available, species-specific conservation programs are implemented with high apparent effectiveness, and are often aimed at reducing species' extinction risk. The goal of most of such targeted conservation programs is to maximize the biological benefits **(**in terms of population size), often through increasing fecundity or survival as fast as possible. Increasing population size is in most cases a necessary and desirable short-term outcome for species-specific programs with large population declines (Kleijn *et al.* 2011). However, such conservation programs that mostly focus on increasing population size commonly neglect programs' biological subtle repercussions (Ferraro and Pattanayak 2006) and economic feasibility over long-time scales (Naidoo *et al.* 2006). In the cases where above factors are ignored, conservation programs may operate as conservation traps, expensive palliatives that, when ceased, would return the species to its endangered status so the money would have been spent in vain (Cardador *et al.* under review).

Cardador *et al.* (under review) defined a conservation trap as conservation strategy where the species would suffer unduly when the adopted measures are stopped, thus perpetuating the need of their implementation, but where the likelihood of maintaining them is low. To avoid conservation traps, species-specific conservation programs must be based on actions that i) prevent species long-term dependence on active intensive management and ii) have high likelihood of maintenance according to its costs (Cardador *et al.* under review). In other words, the programs´ financial sustainability should be given as high consideration as the biological sustainability in order to ensure long-term impacts. Considering biological and economical aspects simultaneously will maximize the chances of choosing management options that are both economically and ecologically sustainable; however, assessing both aspects is not always easy and is rarely, if never, done.

Few conservation programs are systematically tracked over time (Ferraro and Pattanayak 2006; Pullin and Knight 2001) and even fewer are evaluated in their effectiveness (Kleiman *et al*. 2000). This lack of information restricts the assessment of species' benefits and their dependence on conservation programs, and has sometimes led to inefficient spending of conservation resources (Griffith *et al*. 1989; Dodd & Seigel 1991). Further, many of the recorded programs have failed to reduce the species' threats while increased species dependence on management, even in expensive programs where population sizes have increased (Laycock et al. 2011). The absence of a thorough evaluation has at times contributed to maintain ineffective, and sometimes counter-productive, conservation programs. A typical example for this the black robin (*Petroica traverse*) breeding program that weakened the natural selection pressure through intensive species management and contributed to the spread of a maladaptive trait in the species (Massaro *et al*. 2013).

Conversely to the unevaluated biological benefits of conservation programs, more and more conservationists have realized the crucial role of assessing programs' economic feasibility. Nowadays, cost-effectiveness analyses are considered as crucial to evaluate program`s suitability (Laycock *et al*. 2011, Pullin and Knight 2001, Ferraro and Pattanayak 2006). Their application leads to conservation programs that maximize the conservation benefits at the lowest cost (Duke *et al.* 2014), ultimately ensuring its long-term maintenance. Yet, cost-effectiveness analyses are still insufficiently done in most model systems.

Intensive management programs for the Montagu's harrier (*Circus pygargus*), a widely distributed ground-nesting raptor of open farmland in the Palearctic region, provide a suitable opportunity to explore these issues. Almost half of the Western European population of Montagu's harrier breeds in open fields of the Iberian Peninsula and France (Arroyo *et al.* 2004). However, as for other farmland birds, agricultural intensification during the last few decades has also affected its populations (review in Newton, 2004), mainly due to nest and chick destruction during harvest activities (Arroyo *et al.* 2003). To avoid population declines, the species is protected and managed according to different national or regional conservation programs (Arroyo *et al.* 2003). Even if these programs have been effective in increasing productivity (Santangeli *et al.* 2014; Santangeli *et al.* under review) and alleviate population declines, they usually target the species threats by providing short-term solutions (such as nest protection across the whole landscape), whereas a longer-term vision should also be sought. As a result, Montagu's harrier is now dependent on conservation programs for its persistence in most areas of Western Europe (at least where nests occur in farmland, which happens in >70% of nests) (Arroyo *et al.* 2004). In fact, it has been demonstrated that many populations in agricultural areas would locally go extinct without conservation measures (Arroyo *et al.* 2002, Koks and Visser 2002, Santangeli *et al.* 2014).

In Catalonia (NE Spain), the Montagu´s harrier population is mainly distributed in two nuclei, one in Tarragona breeding in natural vegetation (thus without a need of protection during harvest) and another one in Lleida breeding in agricultural landscapes in a mosaic of dry cereal, irrigated cereal and fodder (*e.g. Festuca spp*. and alfalfa *Medicago sativa*) crops. After a strong population decline in the 1980´s, intensive conservation programs started in that region, including a variety of actions (Pomarol *et al*. 1995). Throughout the years, empirical evidence (but not based on quantitative analyses) of what works best (in terms of improving nesting success) led to base the species' conservation program on a market-based approach whereby farmers are paid for delaying harvest of at least half a hectare around the nest (Cardador *et al.* under review; Martínez and Such 2013). In 2005 a strong draught occurred which deemed dry cereal unsuitable for harrier nesting, so harriers moved from their traditional breeding areas to another one with irrigated crops, including fodder, and continued breeding there ever since. However, compensations to farmers for postponing harvest in irrigated cereal and particularly fodder are much higher than in dry cereals, and this has played a major role in the 41% increase in payments per protected nest since 1985 (Cardador *et al.* under review). The current conservation program is thus potentially economically unsustainable for the regional administration in the medium term, and may thus represent a conservation trap in its current form (Cardador *et al.* under review). However, an evaluation of alternative management scenarios at the regional and local level, and whether these would represent an ecological or economic improvement in relation to the current situation, is still lacking.

Here we aim to find a conservation management scenario that decreases the risk of the conservation trap or at least minimizes the medium-term expenditure on conservation, considering simultaneously both natural and agricultural breeding populations in Catalonia. For this, we use population viability analyses to simulate alternative nest protection scenarios based on reduction of conservation efforts on different crop types (*e.g.* fodder, dry or irrigated cereals) in turn and in combination, and with different temporal rates of protection reduction. We quantified the overall biological benefits (in terms of final population size) and compensation costs of each scenario to assess the relative cost-effectiveness of each of them. We ultimately aim to find the best management scenario in relation to cost-effectiveness according to different conservation objectives: maintaining a self-sustainable population in the whole Catalonia region vs maintaining population size in the farmland landscape of Catalonia (i.e. in Lleida, one of the two main nuclei where harriers breed in farmland).

1. Methods

1.1 Study site

The study sites were located within the region of Catalonia (SE Spain), specifically in the provinces of Lleida and Tarragona, which support two separate breeding populations of Montagu's harrier holding up to 85% of the Catalonian population (Arroyo and García 2007; Figure 1). A third and fourth breeding nuclei are located in Barcelona and Girona. However, the one in Barcelona consists in only one or two breeding pairs that do not settle every year, and the population in Girona consists in only 2 to 5 pairs breeding in natural and agricultural habitats (Fortià 2012 & 2013). Due to their small size, Barcelona and Girona breeding pairs were excluded from our analyses.

The population of Lleida is strongly dependent on intensive management given that individuals breed within a mosaic of fodder, dry cereals and irrigated cereals; only a few pairs here breed in natural vegetation, mainly *Juncus spp.* patches occurring between crop fields (Cardador *et al.* under review). Each breeding crop type (dry cereal, irrigated cereal, fodder) is associated with a different productivity (number of fledglings per nest) in the absence of protection (due to different harvest dates for each), and different costs for protection through payments for delaying harvest, as cereal yield is higher for irrigated cereal, and crop value per kg is much higher for fodder than for cereal.

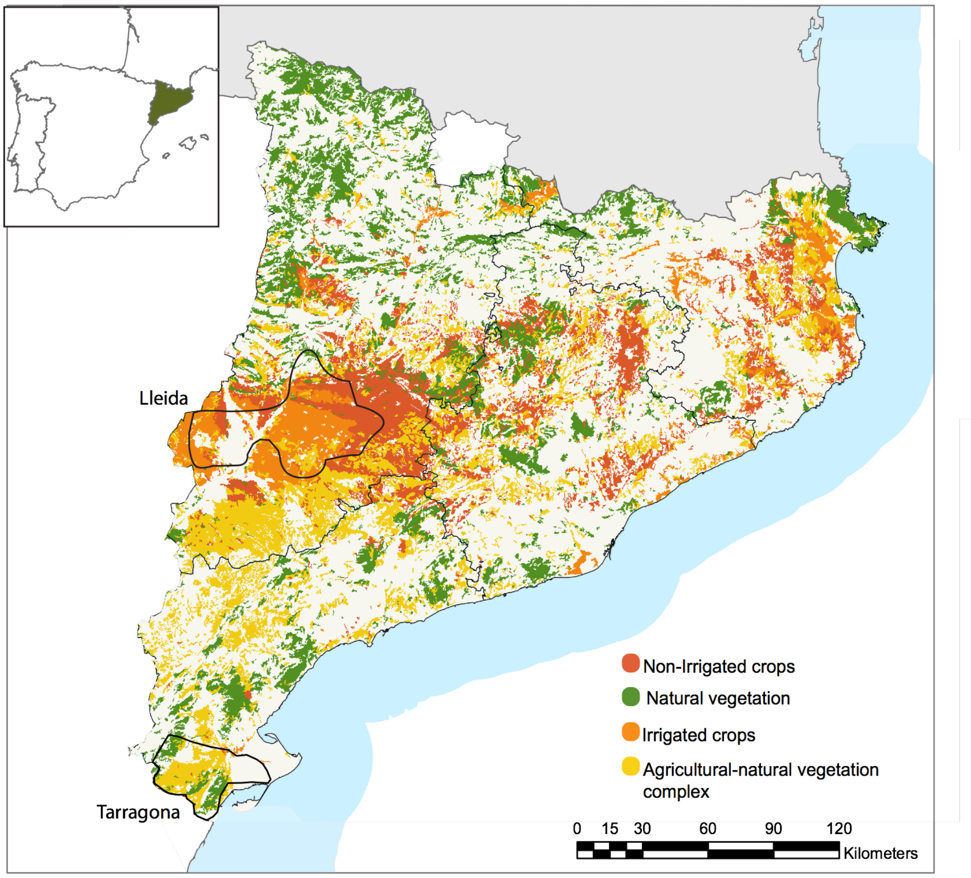

Figure 1. The study area in Catalonia (SE Spain) showing the two areas selected for study with breeding Montagu´s harrier populations in Lleida and Tarragona (within black lines). Information of the land cover was obtained from European Environment Agency 2010).

Harriers in Tarragona breed only in natural vegetation (Mediterranean scrub areas) despite the presence of cereals in the region; therefore they are not target of any nest protection scheme (Martínez & Such 2012). The population in Tarragona established in the early 1990´s, has been stable at around 20 breeding pairs during the past two years, however it can hold the double of pairs as was reported in 2006 (Arroyo & García, 2007). Moreover, its population is likely to increase due to both local recruitment and the dispersal of individuals from the neighboring natural vegetation breeding population of Castellon, which has strongly increased in the last 30 years, and it is still growing (Limiñana *et al.* 2006; Soutullo *et al*. 2006; Oro *et al*. 2012). The landscape in Tarragona has more probability to remain stable than the farmland system in Lleida, as many of the current breeding sites in the former are included inside Natura 2000 (Martínez & Such, 2012).

The two breeding populations of Lleida and Tarragona are approximately 120 km far from each other and are connected by natal dispersal (Figure 1).

1.2 Alternative conservation management scenarios

In order to assess whether it is possible to avoid the conservation trap, we simulated the effects of applying eight different nest protection scenarios for Lleida's population, the only population where protection is applied. We first built two contrasting scenarios. The first assumes business-as-usual where nest protection continues in all crop types (*e.g.* irrigated cereals, dry cereals and fodder) as currently for the next 30 years (*All Prot*). A second scenario simulates the situation where all nest protection stops simultaneously in all crop types (*All Unprot*). With the comparison of these two scenarios we aimed to confirm the necessity of nest protection.

As *All Prot* has been proposed as a possible conservation trap (Cardador *et al.* under review) and stopping all protection (*All Unprot*) might have highly detrimental consequences, we simulated alternative scenarios in between the two above extremes. To know the biological benefit of protecting nests in each crop type, we simulated the protection of nests in only one crop type at a time (*e.g.* nest protection only in fodder (*F*) or dry cereal (*Dc)* or irrigated cereal (*Ic*)) after the first year and during the following 30 years, leaving all other nests unprotected. To get a complete range of conservation options covered by our scenarios, we also evaluated scenarios assuming full nest protection in two crop types simultaneously (using all three possible combinations of two crop types), leaving the third one unprotected. In this sense, we evaluate the impacts of protecting nests located only in fodder and dry cereal (*F+Dc*), or in fodder and irrigated cereal (*F+Ic*), or in dry and irrigated cereal (*Dc+Ic*) after the first year.

Additionally, we simulated 12 additional scenarios considering four different rates of nest protection decrease. This allows assessing if the rate at which nest protection is reduced (in the event of a decision to stop protection) influences the population trajectories in the medium-term. We defined instantaneous rate as the stop of nest protection after the first year. The other three rates consider the reduction of nest protection by a rate of: i) 5% annually in a given crop type, thereby all nests in that crop will be left unprotected after 20 years (hereafter called "slow" rate); ii) 10% annually, so that all nests in previously protected crops will be unprotected after 10 years ("moderate" rate) and iii) 20% per year, so that all nests in that previously protected crop will be left unprotected after 5 years ("fast" rate). We applied these rates to assess the effects of stopping nest protection in all crop types simultaneously (*All Unprot*). Also, and as we assumed nest protection in fodder represents the major driver to the conservation trap (given its difference in productivity according to its protection status, Table 1, and higher costs), we also simulated scenarios that include full nest protection in dry and irrigated cereals (separately or merged together; *Dc, Ic, Dc+Ic*) and decrease in the protection of nests located in fodder at these four different rates.

All scenarios were practically done by changing the relative fecundity for Lleida´s population during the following 30 years except the scenario where conservation continues as currently (*All Prot*), which had a constant fecundity value through the simulation period. Relative fecundity for each conservation program was calculated according to the proportion of protected and unprotected nests in each crop type (fodder, irrigated cereal, dry cereal) and its associated productivity. Average productivity was retrieved from annual nest monitoring data from 1986 until 2012 for Lleida population, and from 2007 until 2013 for Tarragona; these data includes productivity differences between each crop type and protection status (Catalan Government Wildlife Service; Table 1). Our models are a simplification of reality, as we assumed that the proportion of individuals breeding in each crop remains constant over time irrespective of the protection status. All nests in natural vegetation were assumed to be unprotected. Thus, all conservation programs were identical in terms of the demographic and other life-history parameters (see following section) with the exception of the relative fecundity.

All scenarios were simulated in RAMAS GIS 5.0. The simulation period was set to 30 years (ca. 5-8 harrier generations) with 1,000 replications for each scenario. This simulation time allowed the investigation of the medium-term effects of each conservation scenario and decreased the uncertainties of major landscape changes expected in agricultural systems. For each scenario, we retrieved final abundance and adult male trajectories for populations of Lleida and Tarragona separately and for the whole Catalonian population. The eight basic scenarios were compared in their terminal extinction risk at by Kolmogorov-Smirnov tests, which measure the maximum distance between two extinction-risk curves (*D*), and are reported in supplementary material.

Table 1. Observed productivity of Montagu´s harriers in Catalonia according to breeding habitat and protection status. "Nests" refers to the number of monitored nests in each category on which average values are based. Data from Catalan Government Wildlife Service.

Population	Prot. status	Nests	Productivity	SD
Leida				
Natural vegetation	unprotected	19	2.02	1.17
Dry cereal	protected	227	1.58	0.71
Dry cereal	unprotected	39	0.46	0.98
Irrigated cereal	protected	36	1.73	1.12
Irrigated cereal	unprotected	42	1.42	0.74
Fodder	protected	78	1.44	0.38
Fodder	unprotected	8	0.00	0.00
Tarragona				
Natural vegetation	unprotected	124	1.70	0.28

1.3 Demographic parameters used for all scenarios

To build a default model for all scenarios, we used the same survival estimates used previously for population viability analyses in various Spanish regions (Santangeli *et al.* 2014) (see Table 2). Given that females reach maturity earlier than males (Arroyo *et al.* 2004), we included female and male matrices separately considering three stage classes for females and four for males as in Santangeli *et al.* (2014). Female and male juvenile survival (*i.e.* from fledging to following spring) was set at 0.62±0.12 (mean±SD) as estimated by juveniles tagged with satellite transmitters in Castellon, the neighbouring province of Catalonia (Arroyo, 2009). Female's subadult and adult survival was set at 0.85±0.06, while male's subadult and adult survival at 0.80±0.07 (Santangeli *et al.* 2014). These adult survival parameters retain the difference in survival between sexes reported by Millon and Bretagnolle (2008) for French populations and are similar in magnitude to those used in Arroyo *et al.* (2002).

Fecundity was calculated as the product of the portion of breeding females, times productivity, times nestling sex ratio (Table 2). As Santangeli *et al.* (2014), we assumed that only adults attempt to reproduce, 10% of adult females do not breed and an even nestling sex ratio (50:50). Lleida's average fecundity considered productivity as the current proportion of breeding females in each breeding habitat according to its protection status (17 protected females in dry cereals, 16 protected females in irrigated cereals, 25 protected females in fodder and 4 non-protected females in natural vegetation). Tarragona`s fecundity remains constant in all scenarios.

Table 2. Key demographic parameters used for the population viability analyses of Montagu´s harrier populations in Catalonia.

Survival [a]	**Mean**	**SD**
Juv. survival male	0.62	0.12
Juv. survival female	0.62	0.12
Sub-ad. survival male 12-24	0.80	0.07
Sub-ad. survival male 24-36	0.80	0.07
Sub-ad. survival female 12-24	0.85	0.06
Ad. survival male	0.80	0.07
Ad. survival female	0.85	0.06
Mean fecundity [a]	**Mean**	**SD**
Lleida	0.72	0.05
Tarragona	0.77	0.05
Dispersal [b]		
Lleida-Tarragona	0.03	

[a] Survival and mean fecundity used over all simulations

[b] Dispersal was assumed symmetrical from both populations

Initial population size was based on survey data gathered during 2012 in Tarragona (Martínez and Such 2012) and Lleida (Manel Pomarol, Catalan Government Wildlife Service) (Table 3). Sub-adult abundances within each age class and sex were assumed to follow a stable age structure, and juvenile abundance was estimated after breeding but prior to migration as the product of the adult abundance times average female productivity (set at 0.75).

Table 3. Total population size (number of individuals) breakdown by population and life stages used in the population viability analyses in Catalonia

Age class/Population	**Juv F**	**SA F** 12-24	**Ad F** 24+	**Juv M**	**SA M** 12-24	**SA M** 24-36	**Ad M** 36+	**Total**
Lleida/	47	23	*62*	47	23	16	*62*	279
dry cereal	13	6	17	13	6	4	17	77
irrigated cereal	12	6	16	12	6	4	16	72
fodder	19	9	25	19	9	7	25	113
natural vegetation	3	1	4	3	1	1	4	18
Tarragona/								
natural vegetation	14	7	19	14	7	5	19	86
Catalonia	**61**	**30**	***81***	**61**	**30**	**21**	***81***	***365***

Juv, SA and Ad stand for juvenile, sub-adult and adult, F and M to males and females respectively and the months of age. Population is broken down by the number of individuals breeding in each breeding habitat.

To take into account factors (*e.g.* food abundance) that limit population growth beyond a certain threshold, we used a ceiling model that affects population dynamics only when total population abundance reaches over the carrying capacity (Akçakaya 2005). Ceiling for Lleida population was set at 10% (±15% SD) higher than the total initial population size. Ceiling for Tarragona was set as 100% (±15% SD) higher than the total initial population size, to account for the observed higher values of the population size in recent years. Although somewhat arbitrary, these thresholds for the carrying capacity were justified by past trends in population trajectories in the respective sites which indicate how large population each site might support. Dispersal rates were estimated from unpublished re-sighting data of birds marked in Lleida (Manel Pomarol, Catalan Government Wildlife Service). Unfortunately, capture-recapture data from Tarragona are not available; therefore, dispersal rates between sites were assumed to be symmetrical (Table 2). We considered environmental and demographic stochasticity. Environmental stochasticity was assessed replacing the constant survival and fecundity parameters with random values from a lognormal distribution considering their standard deviation (Akçakaya 2005). Demographic stochasticity was accounted for by drawing the number of survivors from a binomial distribution and the number of offspring from a Poisson distribution (Akçakaya 2005). No catastrophes were considered.

1.4 Cost-effectiveness of different conservation scenarios

We calculated the total compensation cost for all the conservation scenarios with an instant rate of protection decrease only (*All Prot, F+Dc, F+Ic, Ic+Dc, A, Dc, Ic* and *All Unprot)*. Overall costs per scenario were calculated as the total number of nests to protect across the period of 30 years times the cost of harvest delay in each crop type where each nest located in Catalonia (because protection costs varied according to crop type). Adult male numbers were always smaller than that of adult females across the scenarios. Assuming that all adult males bred, adult male abundance was used as a proxy for the number of nests. Compensation costs per nest were fixed through the simulation period as 360€/nest for dry cereals, 500€/nest in irrigated cereals and 700€/nest for fodder as reported previously in Cardador *et al. under review.*

We quantified the cost-effectiveness of implementing each above scenario across a 30 years period in Catalonia. Cost-effectiveness of each program was calculated as the ratio between average costs per nest over 30 years and overall final population size, in relation to the baseline cost-effectiveness of the scenario where all nests are left unprotected from the first year (*All Unprot*). Conservation programs with a cost-effective ratio of zero or close to zero are cost-effective; the higher the ratio, the least cost-effective is the scenario.

1.5 Sensitivity analyses

In order to assess the relevance of each parameter into the population trajectories we ran sensitivity analyses for the same conservation programs where budget was estimated. We simulated a ±5 and ±10% change in adult, subadult and juvenile survival simultaneously and separately, as well as, ±5 and ±10% change in fecundity and carrying capacity separately and 5 and 10% increase in dispersal in both populations simultaneously. All results were compared in its terminal extinction risk by Kolmogorov- Smirnov tests. All sensitivity analyses and tests were run in RAMAS GIS 5.0 (Akcakaya 2005). These sensitivity analyses are reported in the supplementary material.

Moreover, all our scenarios assume a closed Catalonian population; however, and although the number of breeding pairs has remained stable in Tarragona over the past three years, it might increase given the high productivity and capacity of dispersal of the growing population in Castellón, the neighbouring province (Limiñana *et al.*, 2006; Oro et al. 2012). To include this possible population increment, and to investigate the impacts of applying a conservation scenario in Catalonia where carrying capacity in the natural breeding population is increased, we ran three additional sensitivity analyses that explore the influence of increasing 150 %, 200 % carrying capacity only in Tarragona when all nests in Lleida remain unprotected (*All Unprot*).

3. Results

3.1 Population consequences of alternative conservation management options

According to the PVA simulation and given the demographic parameters used, the Catalonian population size is expected to increase 21%, from 365 individuals to 440±52 (mean ± SD), during the following 30 years if nest protection is continued as currently done in Lleida's cultivated land. In contrast, if all nest protection would be instantaneously interrupted in Lleida, the Catalonian population would decrease 41% from its current population size (see *dark dashed line,* Figure 2), resulting in about half of the total population size achieved at the end of the 30 years period if protection was applied to all nests in Lleida. This regional decrement is explained by the local reduction of harrier population size in Lleida. In this site, the population would drop from 279 to 66 individuals after 30 years under the *All unprot* scenario (Figure S1), which represents 76 % less individuals than what is expected under the *All prot* scenario (compare *dark solid* and *dashed lines* in Figure S1). On the other hand, harrier population size in Tarragona would increase from 86 up to 151 individuals during a 30 years period, even if all nests in Lleida remain unprotected (*All unprot*), which is only 10 % fewer individuals than expected if conservation continues as currently in Lleida (*All prot* scenario; compare *dark solid* and *dashed lines* in Figure S2). Although the *All unprot scenario* yields the most severe population declines, its application does not lead to local nor regional extinctions within the time period considered (see *dark dashed lines* in Figures 2, S1 and S2).

All alternative scenarios indicate that a reduction in nest-protection at any one or a combination of crop types leads to lower immediate and medium-term biological benefits than the *All prot* scenario in Catalonia (see Figure 2). All scenarios have a different terminal extinction risk (reported in the supplementary material, Table S1), but none of them leads to local or regional extinction during the simulated time frame.

The PVA simulations show that nest protection of each crop type has different biological benefits in Catalonia as a whole and within the two sites separately in the medium-term. Among the scenarios where protection is only applied to nests in a single crop type at a time, nest protection in fodder only (scenario *F, i.e.* all nests in other crop types are left unprotected) yields a final population size (370± 70) which is 27% larger than if protection was applied only to nest in dry cereals (291±64) and 62% larger than in irrigated cereals (229±48; see Figure 2-I). In fact, final population size was lower than current population size, i.e. leads to population decline, in the latter two cases. Interestingly, protection of nests in irrigated cereals (*Ic*) only yields 5 % larger final population size compared to a situation where nests in all crops are left unprotected (*All Unprot*). Overall, focusing nest protection solely on nests in one crop type would lead to a Catalonian population size lower than that if maintaining protection in all three types of crops, as currently done, and protecting nests in either dry or irrigated cereals alone would lead to population declines.

Conversely, protecting nests in two crop types simultaneously yields to medium-term higher biological benefits than if only one crop type is protected, and it leads to stable or increased populations in each case where fodder is also protected (see Figure 2-II). Scenarios that include nest protection in fodder and any cereal yields bigger biological benefits than the protection of both cereals simultaneously. Protecting nests in fodder and dry cereal (*F+Dc*) is the scenario yielding the highest final population size (431±59 individuals); only 2% less than if all crops are protected. Protecting nests of both cereals simultaneously (*Dc+Ic*) would lead to a 14% decrease in population size after 30 years.

Moreover, our results show that slow rates of reduction in protection (i.e. 5% reduction in nest protection from year 1 to year 20) at all crops or exclusively in fodder causes a delay in population declines and thus yields higher final population size at year 30 compared to the scenarios where protection is terminated instantaneously (i.e. from year 1 all nests are left unprotected; see Figure 2-III, IV, V, VI). Stopping protection in all crops will reduce the population irrespective of the rate at which nest protection is halted (see Figure 2 III). Depending on whether the rate of protection reduction is fast, moderate or slow, the Catalonian population would drop by 39%, 37% or 30% from the initial size. This pattern is consistent also in the other scenarios where different rates of protection termination were applied to nest protection in fodder (see Figure 2-IV, V, VI). However, in the latter, different rates of reduction in protection (i.e. instant and fast, or fast and moderate rates) have the same terminal extinction risk (reported in the supplementary material, Table S2).

In all scenarios, the Catalonian population decline reflects the trend of the population in Lleida, which is the only site in Catalonia where nest protection is applied, but differs in the absolute population sizes (due to the population of Tarragona). In this sense, Catalonia and Lleida show similar population trajectories for each given scenario (see Figure 2 and S1); however, given that carrying capacity was set only as the initial population size plus 10% , the population in Lleida does not measurably increase from its current size at the medium-term even when all nests remain protected (*All Prot*; Figure S1). Conversely, population trajectories in Tarragona, which is the population breeding almost exclusively in natural vegetation, are only marginally affected by changes in nest protection efforts in Lleida (see Supplementary material Figure S2).

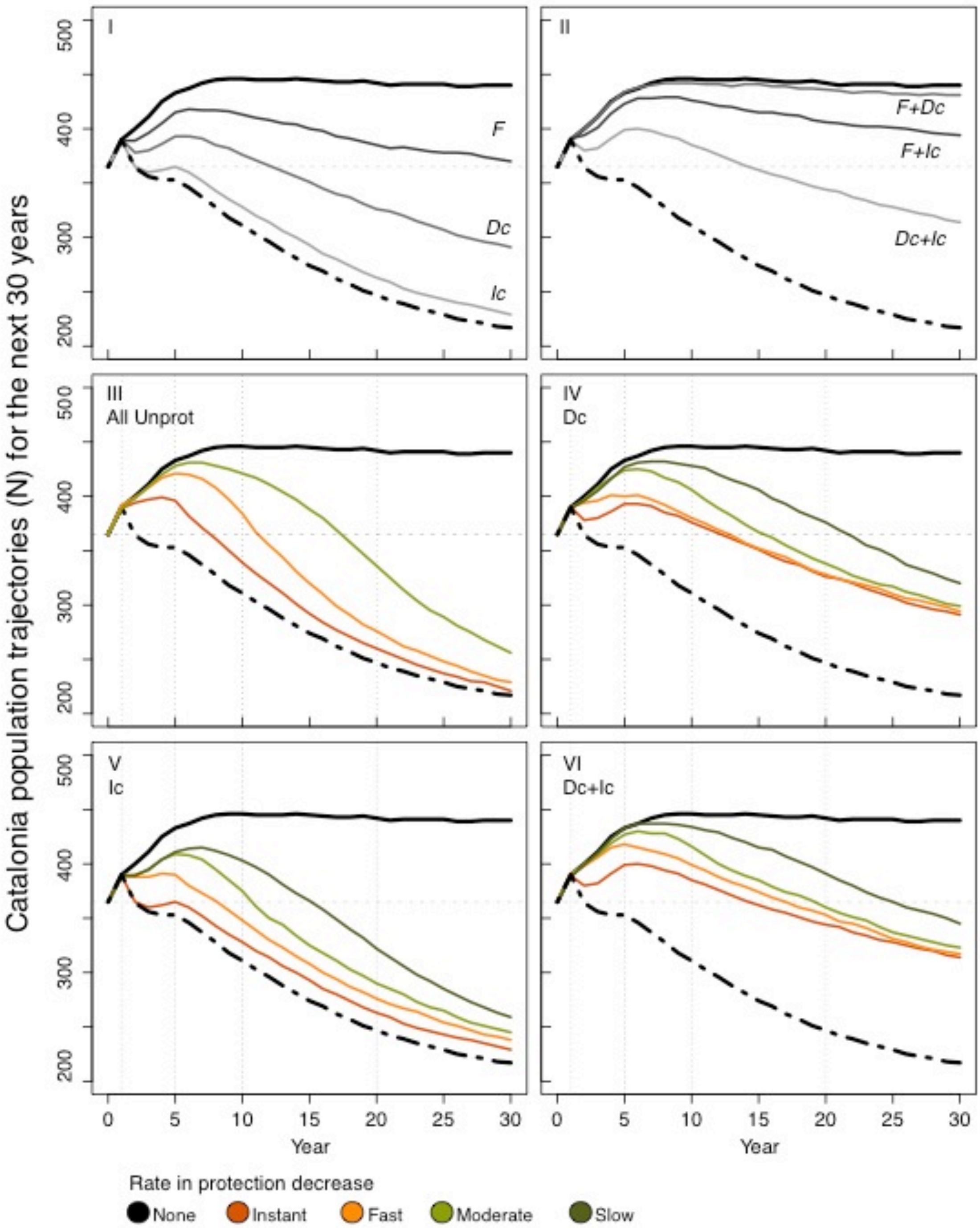

Figure 2. Effects of implementing different nest-protection conservation scenarios in Lleida during the following 30 years on Montagu's harrier average trajectories in Catalonia

(Black solid line represents the nest protection in all crop types (*All Prot*) while the black dashed-pointed line represents the population trajectory if all crops remain unprotected instantaneously (*All Unprot).* Population trajectories if *I)* only nests in only one crop are protected (whereas *F* stands for fodder, *Dc* for dry cereal and *Ic* for irrigated cereal), or if *II)* only two crop types are protected (top-right; whereas *F+Dc* stands for nest protection in fodder and dry cereal, *F+Ic* in fodder and irrigated cereal and *Dc+Ic* in dry and irrigated cereals simultaneously). Remaining graphs show the effect of applying different rates of protection decrease of nests located in *III*) all crops (*All Unprot*) or reducing protection exclusively in fodder while all nests in *IV)* dry cereals (*Dc*), *V)* irrigated cereals (*Ic*) or *VI*) both cereals (*Ic+Dc)* remain protected. Light-dotted vertical lines show the years when protection is fully stopped according to each rate in nest protection decrease. Light-dashed horizontal line shows the current Catalonian population size.)

3.2 Cost-effectiveness

In general, investing more money in nest protection leads to proportionally larger populations that will in turn require more money for protecting an increasing number of nests within a positive feedback loop (Figure 3). However, it is important to also investigate where such increases in population size occur, and where resources are allocated. Costs vary greatly between scenarios owing to their different population sizes and different protection costs at each crop type. Continuing conservation under the *All Prot* scenario would require the biggest budget to cover its compensation costs over a 30 year period (858 151 €; see *All Prot* in Figure 3). This cost is 27 times bigger than the budget required if all nests are left unprotected from year 1 (31 507€ see *All Unprot* in Figure 3).

When assessing exclusively for the compensation costs, management scenarios that involved protecting nests in fodder, alone or in combination with protection at other crop types, lead to higher overall costs than those protecting in any of the cereals alone or in combination (see *black line* in Figure 3). In this sense, protecting nests in fodder alone (*F*) is 112 518 € overall more expensive than protecting nests in dry and irrigated cereals simultaneously (*Dc*+*Ic*), and three times more expensive than protecting nests in either dry (*Dc)* or irrigated (*Ic*) cereal separately. Protecting nests in dry cereal (*Dc*) is the cheapest scenario, requiring 164 276 € for covering its compensation costs over the next 30 years. Previous compensation budget is only 9 401 € less expensive than protecting nests in irrigated cereals (*Ic*), the second cheapest scenario (see Figure 3). However, the assessment of the costs without considering its effectiveness might be misleading.

If the overall conservation objective for the region of Catalonia is to increase the Montagu´s harrier population during the next 30 years, then the most cost-effective conservation scenario is the protection of nests in dry cereals (*Dc;* see Table 4). This scenario has the highest return in terms of population size for the given investment in protection. However, protecting nests in fodder and dry cereals simultaneously and in fodder alone appeared as the second and third best cost-effective scenarios (Table 4). These scenarios are, however, associated to very different absolute costs and biological benefits. Protection in dry cereals is overall three and four times cheaper than protection in fodder (*F)* and *F*+*Dc* respectively, but yields to lower population sizes than the scenarios that include protection of fodder (see Figure 3).

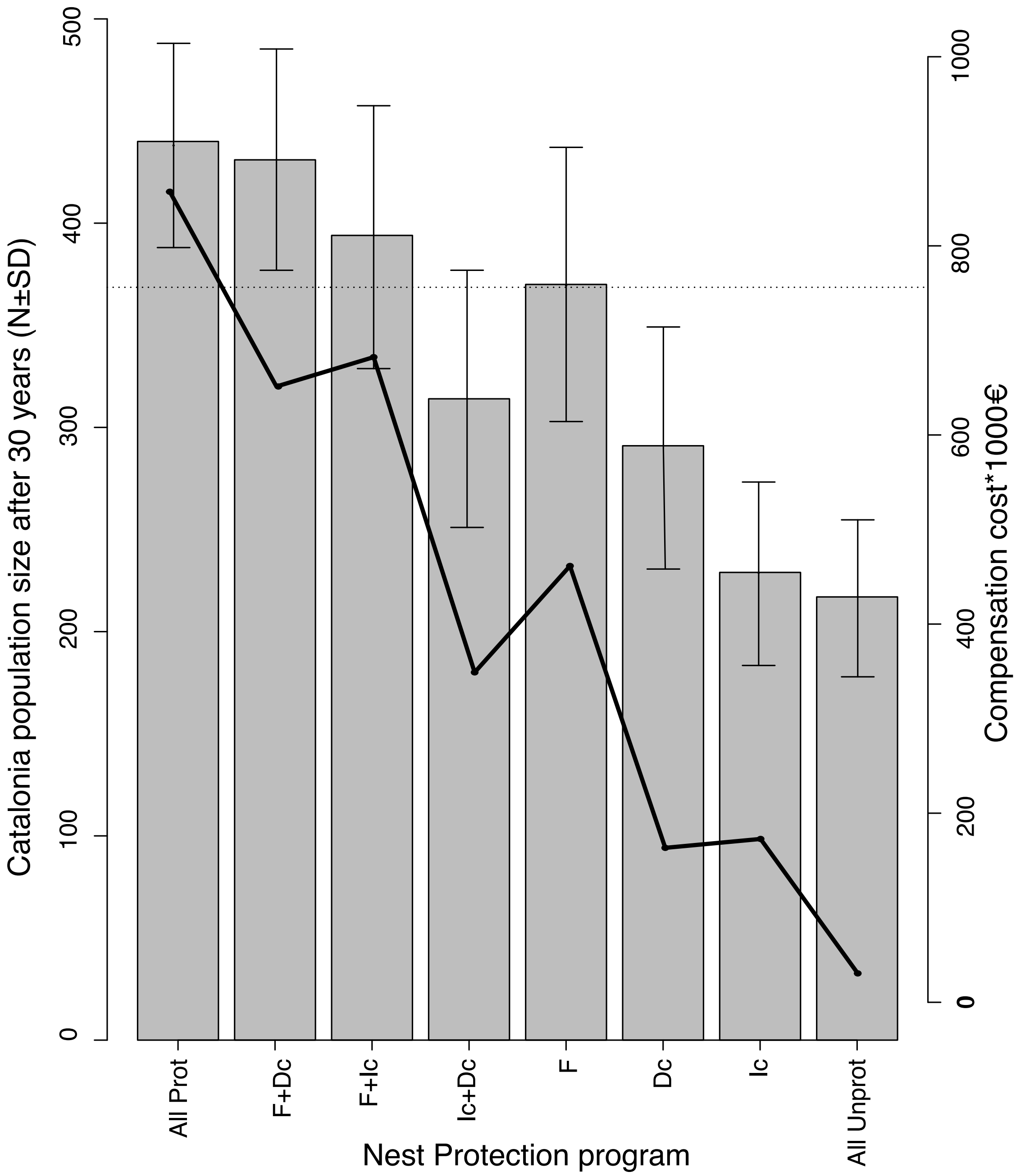

Figure 3. Montagu's harrier final population size and associated budget of developing each nest-protection conservation programs for 30 years in Catalonia

(Bars represent Catalonian population size after 30 years (mean±SD), dotted horizontal line depicts the initial population size and black continuous line represents the associated compensation budget (€) of carrying out each scenario for the following 30 years. Nest protection in all crop types (*All Prot*), in both, fodder and dry cereal (F+*Dc*), fodder and irrigated cereal (F+*Ic*) and irrigated cereals and dry cereals (*Ic*+*Dc*), only in fodder (F), dry cereals (*Dc*), irrigated cereals (*Ic*), and leaving all nest unprotected (*All Unprot*))

Our results indicate that protecting nests in irrigated cereals, either alone or in combination with protection of nests in another crop type, always yields the least cost-effective solution among all scenarios (Table 4). The associated costs per nests for protecting nests in irrigated cereal (*Ic*) alone for 30 years is five times more expensive and would only gain 12 more individuals than if all nests remain unprotected after the first year.

Table 4. Cost-effectiveness and mean cost per nest for the following 30 years of different conservation programs

(Cost-effectiveness was calculated as the ratio between the mean cost per nest (cost/nest) and mean number of individuals gained after 30 years of carrying out each scenario relative to the expected number of individuals in *"All unprotected"* conservation program (ΔN). Values closest to zero are the most cost-effective.
Conservation programs considering nest-protection in fodder and dry cereal (*F+Dc*), fodder and irrigated cereal (*F+Ic*) and irrigated cereals and dry cereals (*Dc+Ic*))

	Cost per nest	Δ N	Cost-effectiveness
All Protected (*All Prot*)	510	223	2.28
F+Dc	385	215	1.79
F+Ic	414	177	2.34
Dc+Ic	237	97	2.44
Fodder (*F*)	290	154	1.89
Dry cereal (*Dc*)	112	74	1.51
Irrigated cereal (*Ic*)	141	12	11.91
All Unprotected (*All Unprot*)	16	0	-

Overall, the management scenario that combines relatively high cost-effectiveness, lower overall costs and relatively higher population benefits is *Dc*, followed by *F+Dc* and *F* that enable the maintenance of the current population size.

3.3 Sensitivity analyses

Sensitivity analyses show that, not very surprisingly, all the scenarios are similarly sensitive to changes in most population parameters. In this light, final population sizes are affected at least to a certain degree by 5% increase or decrease in survival, fecundity and carrying capacity (see Figures S3-7; Table S3). However, the magnitude of these population changes varies according to the parameter under scrutiny. Changes in survival (adults, sub-adults and juveniles) have greater effects on final population sizes than changes in the rest of the other parameters (see Figures

S3-5). In fact, all simulated population trajectories are the most sensitive to changes in adult survival (see Figure S3) followed by changes in sub-adult and juvenile survival (see Figure S4-5), fecundity (see Figure S6) and carrying capacity (see Figure S7). In contrast, population trajectories of all scenarios seem to be not sensitive to changes in dispersal (see Figure S8). In any case, even if final population sizes were affected by these changes in parameter estimates, the overall comparative results among management scenarios remained unaffected: stopping protection in all crops led to strong population declines, protection for nests in irrigated cereal only also led to population declines, scenarios that led to higher or similar overall final population sizes than the current were those that included protection for nests in fodder crops, and scenarios with protection for nests in cereal but no fodder led to intermediate final population sizes between the protection of all crops and all unprotected.

Conversely, a strong increase in carrying capacity in Tarragona (leaving carrying capacity in Lleida as originally set) would change the results even if all nests in all crops in Lleida were unprotected (*All Unprot*; see Figure 4). For example, a 50% increase in Tarragona's carrying capacity would yield to 265±50 individuals after 30 years even if all nests in all crops of Lleida are unprotected (*All Unprot*), which represents a 22% increase compared to the basic *All Unprot* scenario where carrying capacity in Tarragona was set as 100% higher than the initial population size (see *bold line* Figure 4-I). The scenario where carrying capacity in Tarragona is increased by 50% over the carrying capacity value used in the basic scenarios, leads to higher population sizes than if nest protection in Lleida is exclusively done in irrigated cereals regardless of whether the rate of protection decrease in fodder is instantaneous, fast and moderate and carrying capacity in Tarragona kept at the default level. Moreover, increasing 100% carrying capacity in Tarragona (over the carrying capacity value used in the basic scenarios) would yield to 311±62 individuals in Catalonia after 30 years, which is 15% less than the current Catalonia population size (see *dashed-dotted line* Figure 4-I).

Therefore, increasing the carrying capacity of Tarragona will affect Tarragona's and Lleida's population trends, and thus Catalonian trends as a whole (see Figure 4-II, III). In Lleida, increasing carrying capacity of Tarragona would retrieve higher population sizes than those expected if nests are protected exclusively in irrigated cereal and carrying capacity is set as originally. In Tarragona, the increase of carrying capacity leads to longer term population stability (see Figure 4-III). In this sense, Tarragona population would stabilize after 10 years if carrying capacity increases 50 % over our basic scenario, which is five years later than if all nests remain unprotected under the default scenario (*All Unprot*) (see Figure 4-III). Additionally, if carrying capacity increases 100% in Tarragona, this population would grow steadily through the first 15 years of the simulation (see Figure 4-III).

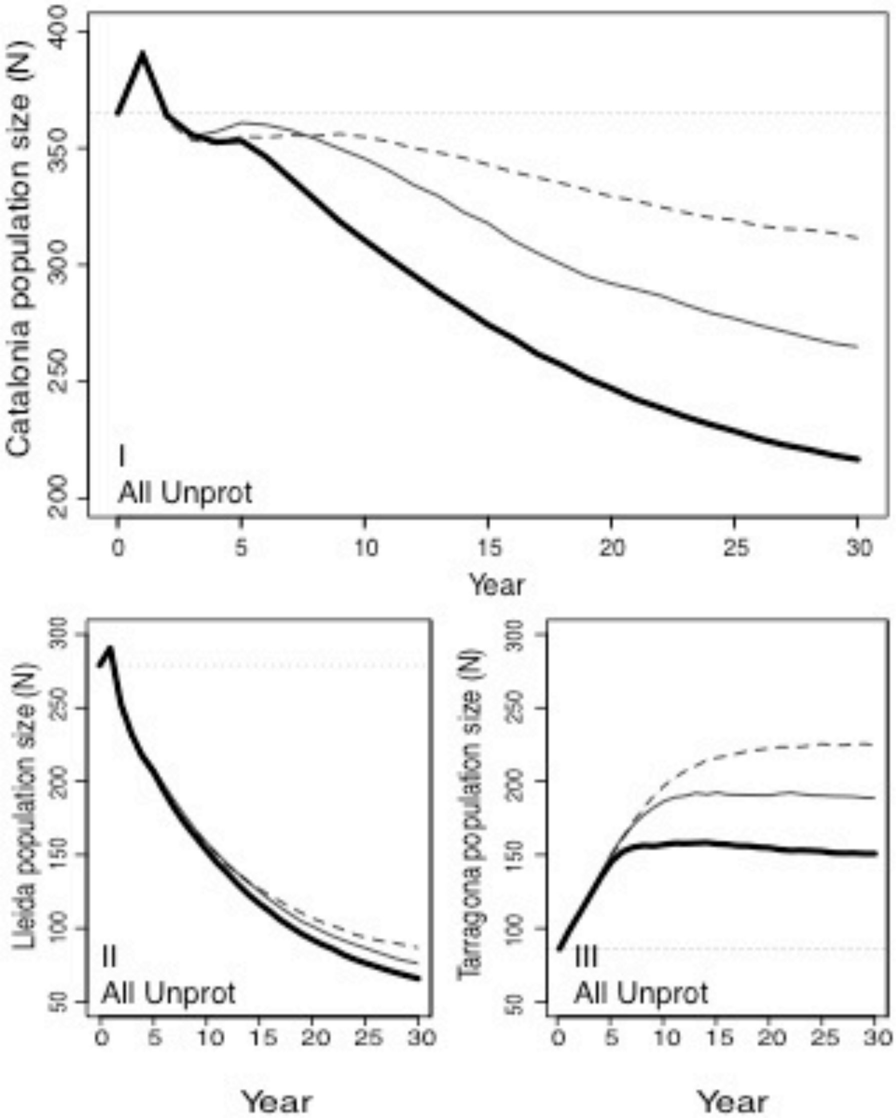

Figure 4. Montagu's harrier average trajectories if Tarragona's carrying capacity increases a 50% (solid thin line) or 100% (dashed line) meanwhile all nests in Lleida remain unprotected (*All Unprot*)
(Bold solid line represents the population trajectories if all nests remain unprotected instantaneously (*All Unprot*) as reported above. Pointed line represents the current population size in each population. Graphs show the effects of increasing Tarragona's carrying capacity a 50 and 100% in *I)* Catalonia, *II)* Lleida and *III)* Tarragona populations. Lleida`s carrying capacity remains the same as 10% more of the initial population size.

4. Discussion

Overall, our results show that increasing protection investment in farmland Montagu´s harriers in Catalonia generally increases population sizes and this will in turn increase the costs for protection in a positive feedback fashion. On the other hand, costs for nest protection and protection effectiveness vary among the different crop types considered, and this variation in cost-effectiveness allows choices to be made between the several scenarios we simulated. It is however important to bear in mind that the results are the outcome of simulations that depend entirely on the demographic and environmental information we inputted. In this light, we call for caution when interpreting the results.

In their recent paper, Cardador *et al.* (under review) put forward the idea of conservation traps using the Montagu's harrier as a case study. They propose that alternative holistic approaches to conservation management should be used to avoid these situations. Here we provide empirical evidence, using PVA, of how to avoid a conservation trap and what this entails in terms of economic sustainability and species persistence.

4.1 Searching for self-sustainability

Our results demonstrate that if the conservation goal is to achieve a **self-sustainable** breeding population in Catalonia, stopping all nest protection in Lleida might be the optimal solution. This scenario would reduce the overall population size from its current state shifting the dependence of Catalonia population from the potentially unsustainable farmland population in Lleida to the natural breeding population in Tarragona. According to our results, applying this scenario would cause a reduction, but not extinction, in the population breeding in farmland in Lleida, whereas the natural vegetation breeding population in Tarragona would increase and stabilize at the medium-term. Accepting population size declines as part of a conservation program might be challenging but, as Cardador *et al* (under review) suggested, financial and biological self-sustainable programs should attempt to solve the conservation problem rather than attempt to preserve unsustainable past or static reference states.

Moreover, the presented Catalonia population trajectory if all nests remain unprotected in Lleida (see *dashed-pointed line* Figure 2) might be underestimated. The sensitivity analyses show that if carrying capacity in Tarragona were higher than

100% more than its initial population size (a highly possible scenario as in 2006 the population size was double as the one used in this study; Arroyo & García 2007), the overall population size would be similar to the expected if nest protection is carried out in both cereal crops (combined or separately) in Lleida. A more accurate estimate of carrying capacity was unavailable as annual population fluctuations may be due to a variety of factors not contemplated in this study, so numbers of breeding pairs observed in 2006 may not represent 90% of carrying capacity in the area. Nevertheless, irrespective of the carrying capacity estimate, if all nests in Lleida remain unprotected, Tarragona population would become a source of individuals compensating in certain degree Lleida´s population sink. A natural increase in population size in Tarragona, thus free of cost, would potentially avoid Montagu's harrier conservation trap in Catalonia.

Catalonian managers have already recognized the importance of natural breeding populations for the whole sustainability of Catalonia's population. However, studies have focused in fixing individuals to inhabited natural vegetation sites in Girona (though the 'hacking' release method; Pomarol *et al.* 1995). This program had poor success (Arroyo & García 2007). Our results show that given the intrinsic characteristics of the population in Tarragona, it might be easier in terms of management to increase this population rather than fixing another population elsewhere. Furthermore, carrying capacity might be artificially increased by actions aiming to expand the habitat availability (*e.g.* surface covered in natural vegetation) and/or quality (*e.g.* food availability) of breeding areas in Tarragona. Increasing carrying capacity in this way will have associated costs. However, costs for developing such kind of scenario were not available, and thus, not included in our cost-effectiveness analyses. If managers aim to increase the natural breeding population in this manner, future investigations should determine the long-term sustainability of those management options.

4.2 Searching for the maintenance of both populations

Our results show that continuing Montagu's harrier conservation for the next 30 years as currently done in Lleida will stabilize the population size, but will be most likely economically unsustainable in the long run owing to the high overall costs (either expressed as the overall budget or the mean cost per protected nest). On the other hand, if protection completely stops at year one, this will have strong negative repercussions on the species population trajectory as evident when contrasting population trajectories of *All Prot* and *All Unprot* in Figure 2. On these basis, our results reinforce previous conclusions that the current conservation program of Montagu's harrier in Catalonia likely represents a conservation trap (Cardador *et al.* under review), whereby nest protection augments overall costs trough time, and if protection is reduced or completely stopped because of budget reductions (a very realistic possibility), the population would decline as a response.

All the scenarios between the *All Prot* and *All Unprot* represent alternative options if the conservation goal is to maintain birds also in farmland. However, our results confirm that if the conservation goal is to **maintain the farmland** breeding population of Lleida or to **maintain** the overall Catalonian population size at the current numbers stopping nest protection in all crops is not desirable. This reinforces the need for active management of the species as reported previously for Catalonia (Cardador *et al*. under review) and for other Spanish populations (Arroyo et al. 2002; Santangeli *et al.* 2014). And although under this goal it is not possible to fully avoid the conservation trap (as the population is not self-sustainable) it is possible to minimize the medium-term expenditure on conservation (therefore increasing the financial sustainability), considering both populations in Catalonia.

Our results demonstrate that continuing protection efforts as currently allocated is not financially viable. In this light, our intermediate scenarios show different ways to achieve better financial sustainability of the conservation program.

Our results demonstrate that protection at each crop yields a different medium-term biological benefit, economic feasibility and risk of species' dependence to its conservation program. Protecting nests in fodder alone or merged with any other cereal (*F+Dc, F+Ic*) would at least maintain the current population size in Catalonia. Although these previous scenarios (*F, F+Dc, F+Ic*) retrieve higher biological benefits and are relatively cost-efficient solutions, they present lowest economic feasibility at the medium-term. The latter is demonstrated by higher final compensation costs and mean cost per nest when compared to the other scenarios. Despite this low economic sustainability, Montagu's harriers select fodder in Lleida because the crop is taller and denser vegetation than the other breeding habitats early in the breeding season (Claro 2000; Arroyo *et al.* 2004). However, this biological pattern might be enhanced by previous successful breeding attempts resulting from the nest protection in fodder. In this sense, continuing conservation in fodder might not only be financially unsustainable but might increase the species dependence on the conservation program.

This discrepancy between the medium-term biological benefits and low self-sustainability of scenarios including nest protection in fodder rises the question whether is best to pursue: a) the largest biological benefits or b) to increase the medium-term economic feasibility while decreasing the species risk to depend on the program and thus to suffer after this terminates because of lack of funding (decreasing the magnitude of the conservation trap). In this sense, we share the view of Cardador *et al*. (in review) for an urgent need to find fresh solutions that would lead to avoid expensive conservation traps. On the other hand, decreasing protection in fodder crops might not be as detrimental as our simulation show. It is possible that after failed breeding attempts due the decrease of protection in fodder, individuals may relocate themselves into respectively more successful breeding sites the consecutive year, thus changing the proportion of nests in different crops. We could not incorporate this possibility in our simulations, but it is worth considering it for future studies.

Our results demonstrate that nest protection in irrigated cereals alone or at any combination of protected crops (*F+Ic, Dc+Ic*) is highly cost-ineffective and might thus be stopped in Catalonia. This poor cost-effectiveness in irrigated cereals relies in the small difference between the productivity of protected and unprotected nests due to late harvest period allowing most chicks to fledge even without protection (Manel Pomarol, pers. Comm.), coupled with a much higher cost per nest than dry cereal. This does not mean that the contribution of irrigated cereals to the final population size is unimportant, it only means that it is not worthwhile paying for its protection. Actually the medium-term survival of the population in Lleida mainly relies in the high productivity of this crop type when it is unprotected (as seen by the small differences between all unprotected and irrigated cereal). In this sense, our results agree with the suggestions of Cardador *et al.* (under submission) where designing a conservation program which favours the increase of breeding pairs in irrigated cereals over other crop types would be an accurate transition program towards self-sustainability of the farmland population in Catalonia.

Finally, our results suggest that protecting nests only in dry cereals is the most cost-effective option if the objective is to maintain the population in Lleida while increasing the medium-term economic sustainability. Moreover, protection in this crop would decrease the risk of species dependence when compared to fodder and would increase Catalonian population size with respect to *All Unprot,* which results from the contribution of the protected nests in dry cereals and unprotected nests in irrigated cereals. In other words, protecting nests exclusively in dry cereal would not avoid but would decrease the magnitude of the current conservation trap in Catalonia. Further, this scenario would allow maintaining harriers in farmland with smallest costs (one fifth of what expected if we continue conservation as nowadays).

Not all our scenarios lead to population stability within the time frame used (Figure 2). Therefore, some scenarios may lead to stronger decreases in a longer time period. Increasing the simulation time might show a stabilizing trend in population but will also increase other uncertainties (other factors affecting populations in the meantime).

4.2.1 Influence of the rate of protection decrease

Our results also show that Montagu´s harrier population persistence would not be affected by the rate of nest protection reduction in Catalonia. This means that, at least theoretically, conservation programs that differ exclusively on their rate of protection reduction might reach to similar population sizes at the medium-term. In this sense, and if the decision is reached about stopping nest protection in a given crop, conservationists should not bother with the rate of protection decrease and save costs by stopping nest protection instantaneously. However, we acknowledge that if the scenarios allowed the movement of individuals to more successful crop types, slower rates of protection decrease would yield higher population sizes than if protection stops instantaneously. Therefore, it is the responsibility of conservation practitioners to take into consideration the rate of nest protection reduction according to program's budget and goal.

4.3 Sensitivity of the results to the parameters used

Our sensitivity analyses demonstrate that, as expected for this type of species, all the scenarios are less sensible to changes in fecundity, carrying capacity and dispersal than to changes in survival. This introduces a certain level of uncertainty in our results that should be born in mind, because survival estimates were not population-specific and might have been overestimated (Santangeli *et al.* 2014). Nevertheless, almost all scenarios respond in the same way to changes in the initial parameters regardless of the estimates used. Furthermore, all conclusions remain the same except for the following: if survival estimates are 5% lower than those used in our scenarios, *F+Ic* would also lead to maintaining the current population size instead of increasing the current population size. This also implies that predictions would not be accurate if conditions in the wintering habitats (and thus winter survival) degrade through time. It has been highlighted that Montagu`s harrier protection in Sub-Saharan Africa urges improvements (Limiñana *et al.* 2012).

4.4 Study limitations

As mentioned before, our model assumes a stable proportion of nests in each crop type or natural vegetation, which is an oversimplification of the reality. Harriers are flexible in their choice of nesting habitats, and the same way they started using irrigated crops in 2005, they may favour one or other of crops at a given moment for a variety of reasons. For example, if protection occurs only in one of the crops, and breeding success is systematically much higher or lower in it, this may influence their choice of breeding habitat, thus modifying the proportion in crop types used with time, and the overall results. Additionally, both climate and farming practices may change both the availability and the attractivity (height and density of the sward at arrival time) of those habitats throughout the study period. It was not possible to include these potential changes of habitat selection through time, but it is important to take into account that they may influence results. Future work could simulate how a variation in this proportion may change our observed trends.

Additionally, here we only presented compensation costs, which are only a fraction of the total costs for each scenario. Total costs would also include costs related to fieldwork for detecting nests. In this sense, the total costs are higher than the presented values. However, the inclusion of fieldwork costs would not affect the relative cost-effectiveness of each scenario, because population monitoring (regardless of intervention) occurs as part of the conservation management for the species in Catalonia (also in Tarragona, for example, where no intervention occurs), and in Lleida only one type of intervention is applied (harvest delay), contrary to other studies where fieldwork costs varied according to the type of protection measure (Santangeli *et al.* 2014). Indeed, fieldwork costs may add variation in our values owing to possible different aggregation levels of nesting harriers in different crop types considered here.

4.5 Broader studies

As in all PVA, here we used demographic-specific parameters. Therefore all our conclusions remain species-specific. However, as seen in our results, the productivity of Montagu´s harrier in farmland clearly depends on the nest protection status and the time harvest is delayed (Santangeli *et al.* 2014). Delaying harvest is a common practice for the protection of other ground nesting birds and shifts on harvest affect productivity of farmland birds in similar ways (Newton 2004). Therefore, if the bird's breeding period is similar to Montagu´s harrier and the harvest timing is similar than in Catalonia, our broad conclusions such as low efficiency of paying for protection of nest in irrigated cereals and increase the risk of increasing the magnitude of the conservation trap if nests in fodder are protected might be similar to other systems.

Selecting conservation scenarios based only on biological targets might not be a good idea because it excludes the associated costs and fails to reduce the species conservation trap. On the other hand, selecting cost-effective scenarios over the medium-term might partially reduce the conservation trap as they reduced the costs and maximize the benefits, increasing the medium-term economic feasibility. However, neither of these conservation goals takes explicitly into account the species' dependence risk to its conservation program. In our view a successful conservation program should explicitly state its conservation goal, account for the biological benefits and costs (as recommended by Botrill *et al.* 2008), and must present low likelihood of dependence to the conservation actions and high economic feasibility over time. In other words it should aim to self-sustainable populations, thus avoiding conservation traps.

5. Conclusion

Based on our results and the demographic parameters considered, for the conservation of Montagu´s harrier in Catalonia we recommend to modify the current conservation program. If the conservation goal is to maintain a self-sustainable population in Catalonia, then all crops in Lleida should be unprotected. In this way, it might be possible to avoid Montagu`s harrier conservation trap in Catalonia preserving both populations at least during the medium-term. However, applying this conservation scenario would dramatically decrease Lleida's population, therefore we urge for future studies assessing the feasibility of increasing carrying capacity in Tarragona or the impacts of protecting nests in Lleida until the Tarragona's population size serves as a major source of individuals to the farmland population. We also recognize that for achieving self-suitable populations, managers should be open to change their reference state targets (past population sizes) even when this change yields to smaller population sizes.

On the other hand, our studies demonstrate that if the conservation goal was to maintain both breeding populations' strongholds in Catalonia (for example, if there are specific aims at maintaining biodiversity in farmland), it would be almost impossible to escape the conservation trap. However, we identify actions that would minimize the medium-term expenditure on conservation, such as, 1) stopping the protection of nests located in irrigated cereal, given that its costs are much higher than its benefits and 2) decreasing or stopping conservation in fodder, given its high cost and the risk of the species dependence to the conservation program. Our analyses suggest the most cost-effective scenario that reduces, but not avoids, the risk of conservation trap while increases the population size with respect to the scenario where all nests are left unprotected is protecting nests only in dry cereals. However, further studies based on simulations changing the proportion of nests in each crop type over time are desirable.

Even if our particular conclusions might not be a general pattern, our investigation shows that detecting a scenario that fully avoids the conservation trap is not easy and depends on the overall conservation objective. However, our investigation demonstrates that it is possible to select conservation scenarios that minimize and may potentially avoid the conservation trap. During this investigation we detect the importance of 1) keeping long-term records of the conservation program, 2) defining clear conservation goals (with explicit targets in time and space) and 3) simulating its long-term biological effects and costs.

In a medium-term vision, a successful conservation program should not lead to a conservation trap. Here we presented how to detect and potentially reduce the risk of the conservation trap by using population viability analyses considering future repercussions on the species dependence and economic costs over time. Our methodology allows the ranking of different effort allocation scenarios according to their associated costs and biological outcomes. However, selection of conservation programs that are not conservation traps should be carefully assessed as neither of the traditional conservation goals (e.g. best biological benefit, most-cost effective) fully avoids the conservation trap. In this sense, conservationists should aim to maintain a sustainable population, which decreases or avoids the risk of the conservation trap.

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7. Supporting material

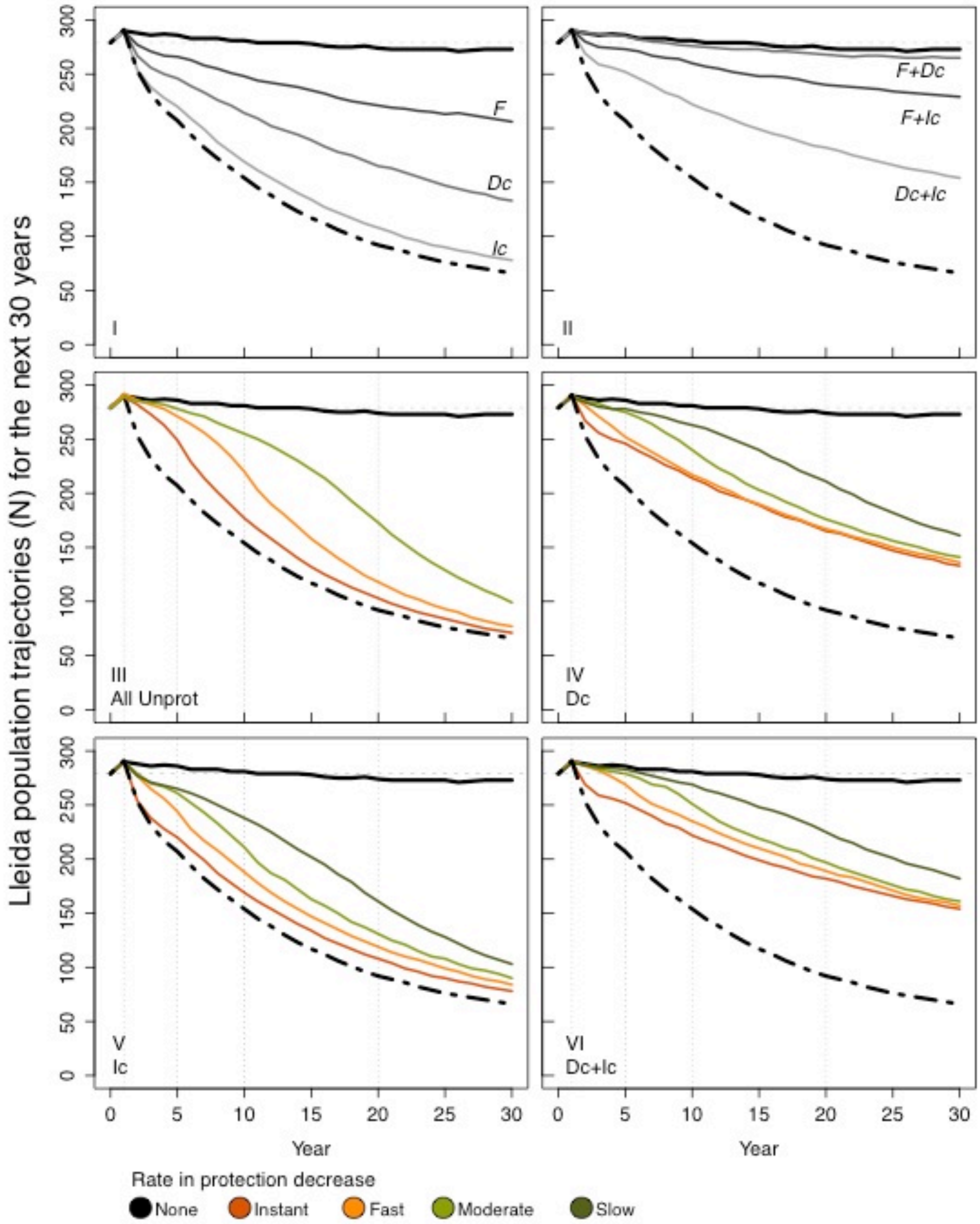

Figure S1. Effects of implementing different nest-protection conservation scenarios during the following 30 years on Montagu's harrier average trajectories of Lleida. Black solid line represents the nest protection in all crop types (*All Prot*) while the black dashed-pointed line represents the population trajectory if all crops remain unprotected instantaneously (*All Unprot)*. Population trajectories if *I)* only nests in only one crop are protected (whereas *F* stands for fodder, *Dc* for dry cereal and *Ic* for irrigated cereal), or if *II)* only two crop types are protected (top-right; whereas *F+Dc* stands for nest protection in fodder and dry cereal, *F+Ic* in fodder and irrigated cereal and *Dc+Ic* in dry and irrigated cereals simultaneously). Remaining graphs show the effect of applying different rates of protection decrease of nests located in *III*) all crops (*All Unprot*) or reducing protection exclusively in fodder while all nests in *IV)* dry cereals (*Dc*), *V)* irrigated cereals (*Ic*) or *VI*) both cereals (*Ic+Dc)* remain protected. Light-dotted vertical lines show the years when protection is fully stopped according to each rate in nest protection decrease. Light-dashed horizontal line shows the current Lleida population size.

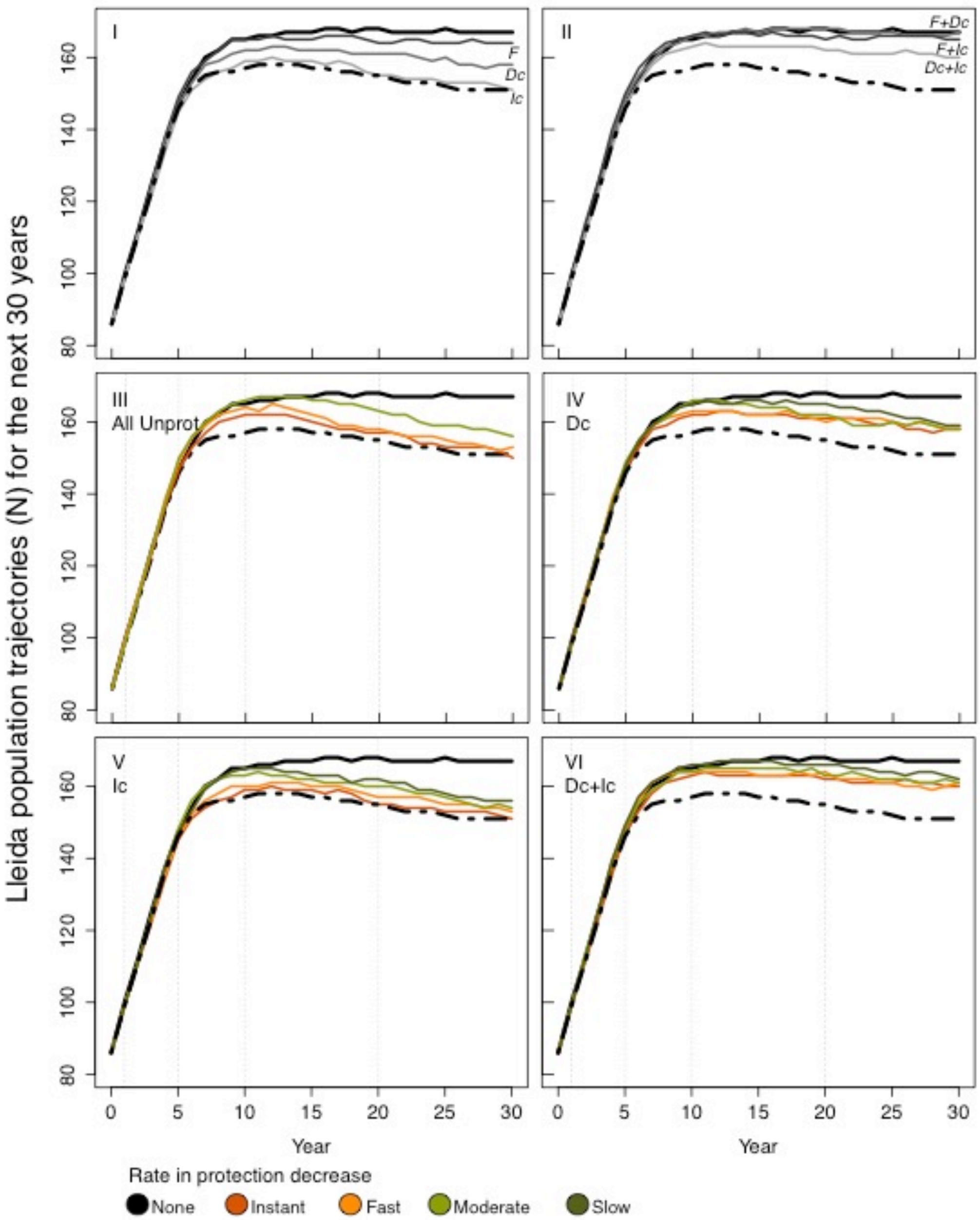

Figure S2. Effects of implementing different nest-protection conservation scenarios in Lleida during the following 30 years on Montagu's harrier average trajectories of Tarragona. Black solid line represents the nest protection in all crop types (*All Prot*) while the black dashed-pointed line represents the population trajectory if all crops remain unprotected instantaneously (*All Unprot).* Population trajectories respond to the scenarios carried out in Lleida if *I)* only nests in only one crop are protected (whereas *F* stands for fodder, *Dc* for dry cereal and *Ic* for irrigated cereal), or if *II)* only two crop types are protected (top-right; whereas *F+Dc* stands for nest protection in fodder and dry cereal, *F+Ic* in fodder and irrigated cereal and *Dc+Ic* in dry and irrigated cereals simultaneously). Remaining graphs show the effect of applying different rates of protection decrease of nests located in *III*) all crops (*All Unprot*) or reducing protection exclusively in fodder while all nests in *IV)* dry cereals (*Dc*), *V)* irrigated cereals (*Ic*) or *VI*) both cereals (*Ic+Dc)* remain protected. Light-dotted vertical lines show the years when protection is fully stopped in Lleida according to each rate in nest protection decrease.

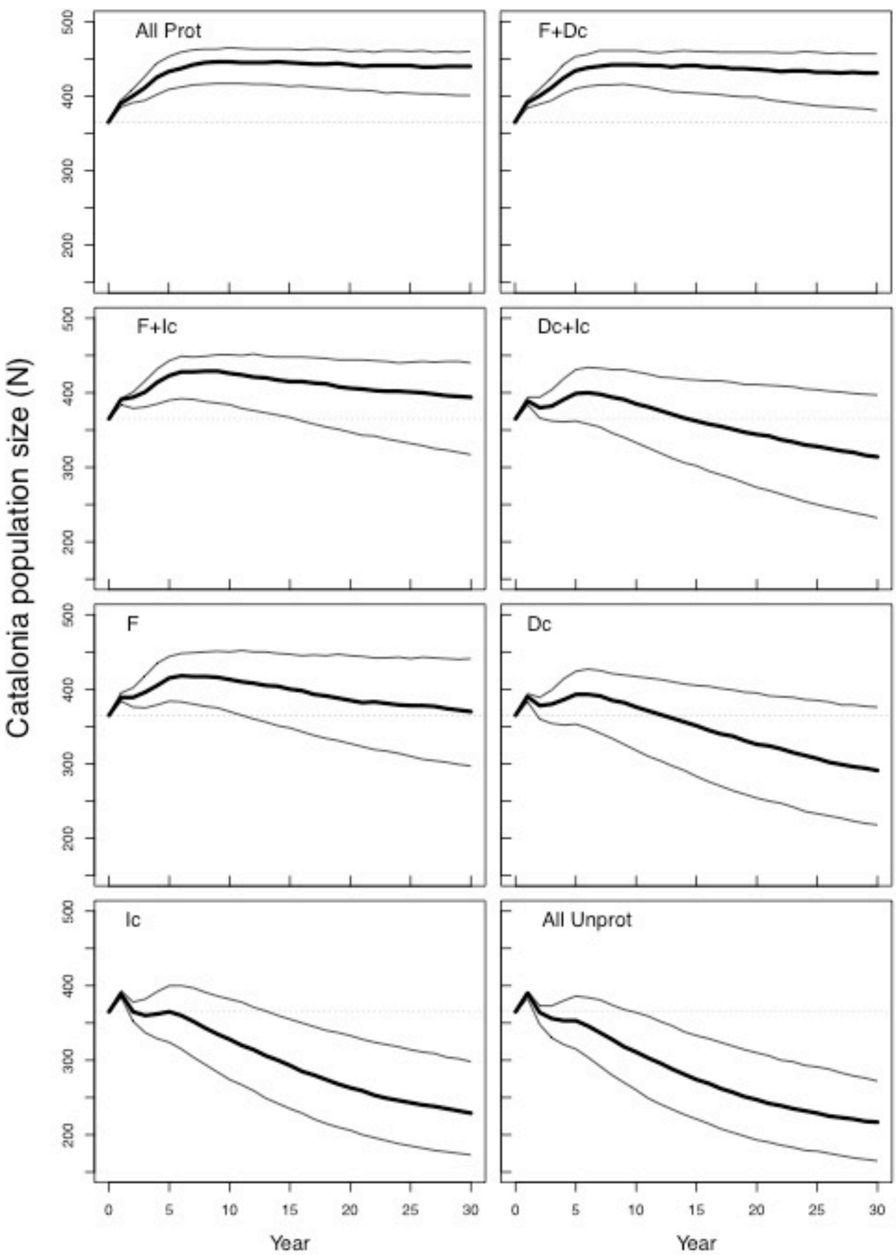

Figure S3. Sensitivity of Catalonian population trajectories for the following 30 years to variations of 5% increase (upper thin line) and 5% decrease (bottom thin line) in **adult survival** according to each conservation program. Thick solid lines denote the average trajectory of Catalonian population size (as figure 2-I and II in the main text), dotted lines represent the initial population size. All trajectories have different terminal extinction risk.

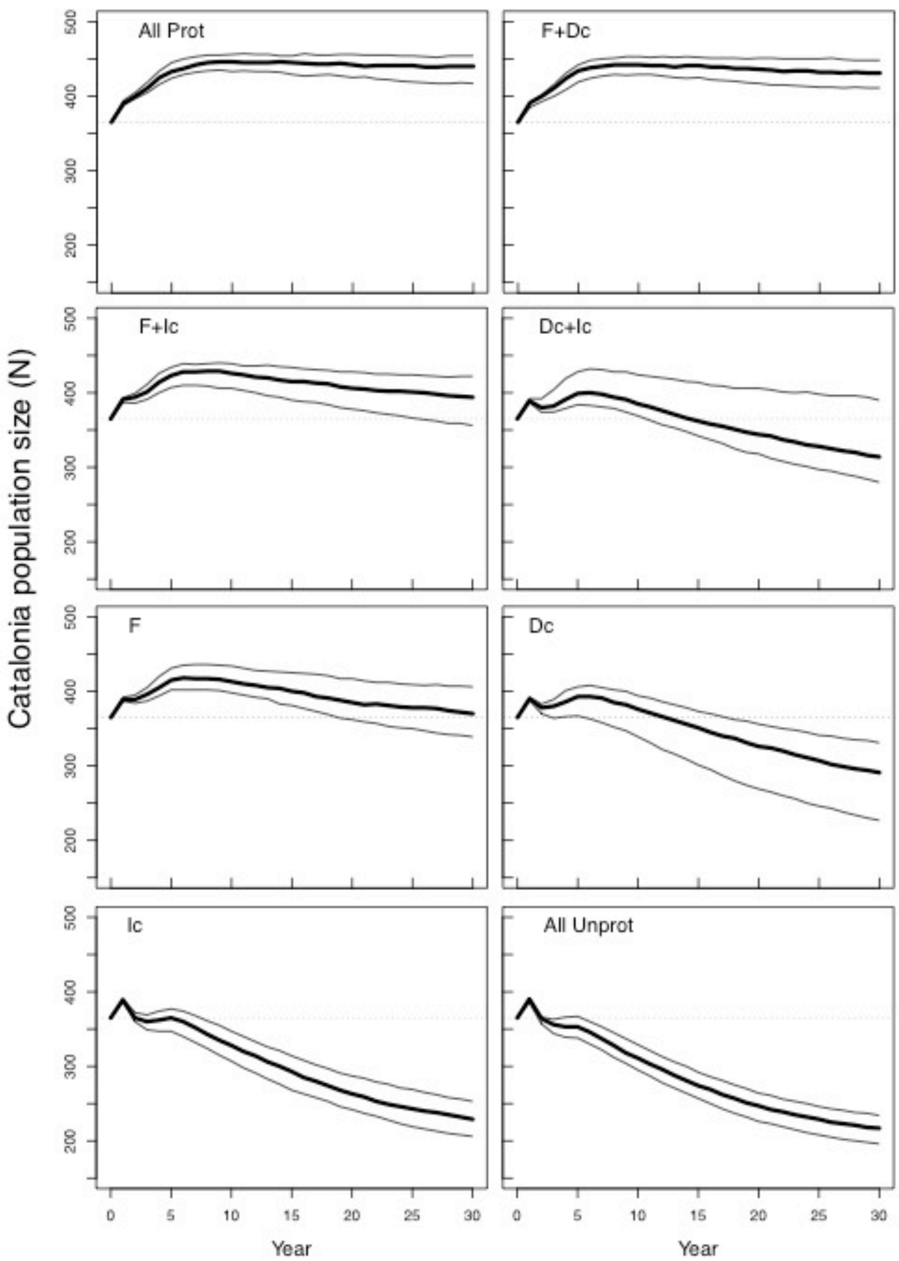

Figure S4. Sensitivity of Catalonian population trajectories for the following 30 years to variations of 5% increase (upper thin line) and 5% decrease (bottom thin line) in **sub-adult survival** according to each conservation program. Thick solid line represents the average trajectory of Catalonian population size (as figure 2-I and II in the main text), dotted lines represent the initial population size. All trajectories have different terminal extinction risk.

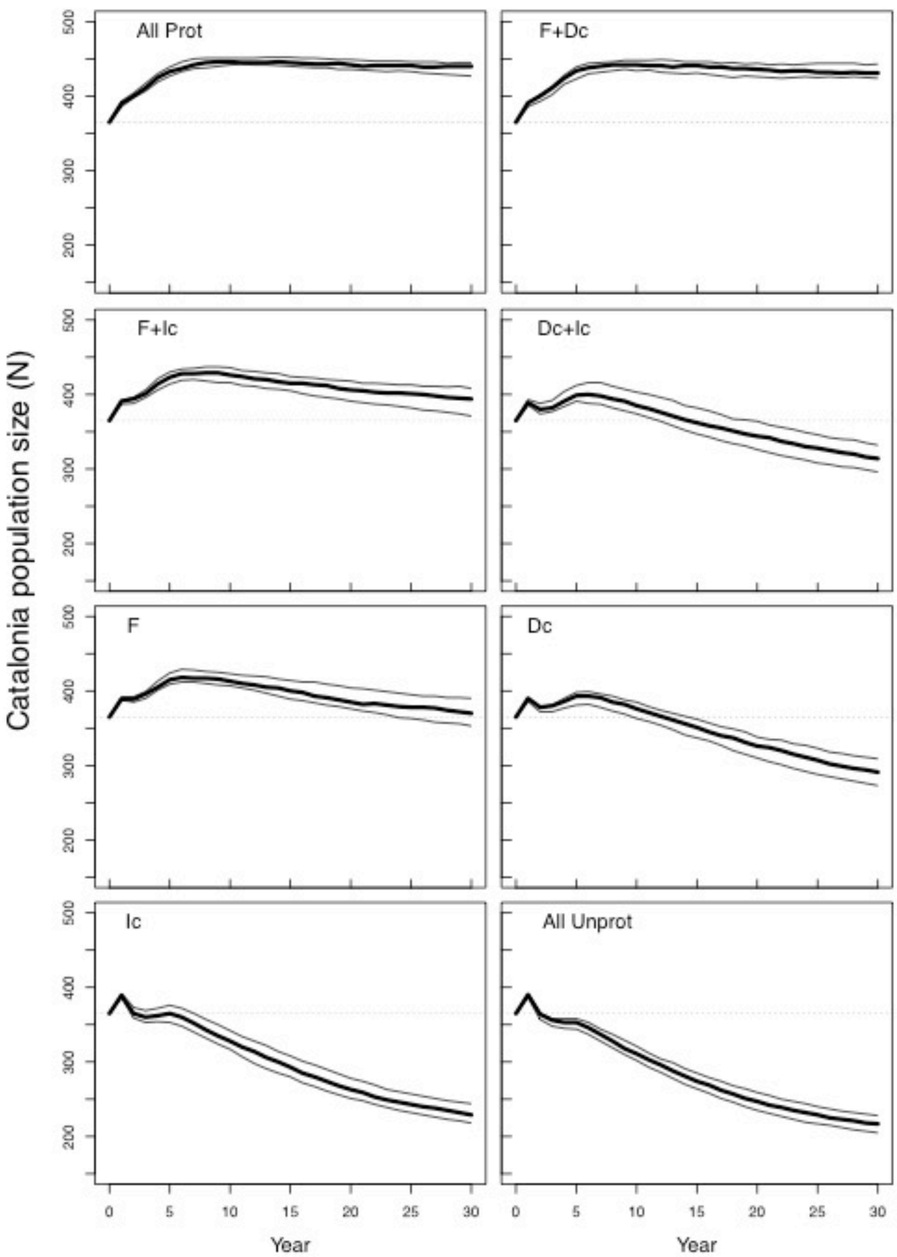

Figure S5. Sensitivity of Catalonian population trajectories for the following 30 years to variations of 5% increase (upper thin line) and 5% decrease (bottom thin line) in **juvenile survival** according to each conservation scenario. Thick solid line represents the average trajectory of Catalonian population size (as figure 2-I and II in the main text), dotted lines represent the initial population size. All trajectories have different terminal extinction risk.

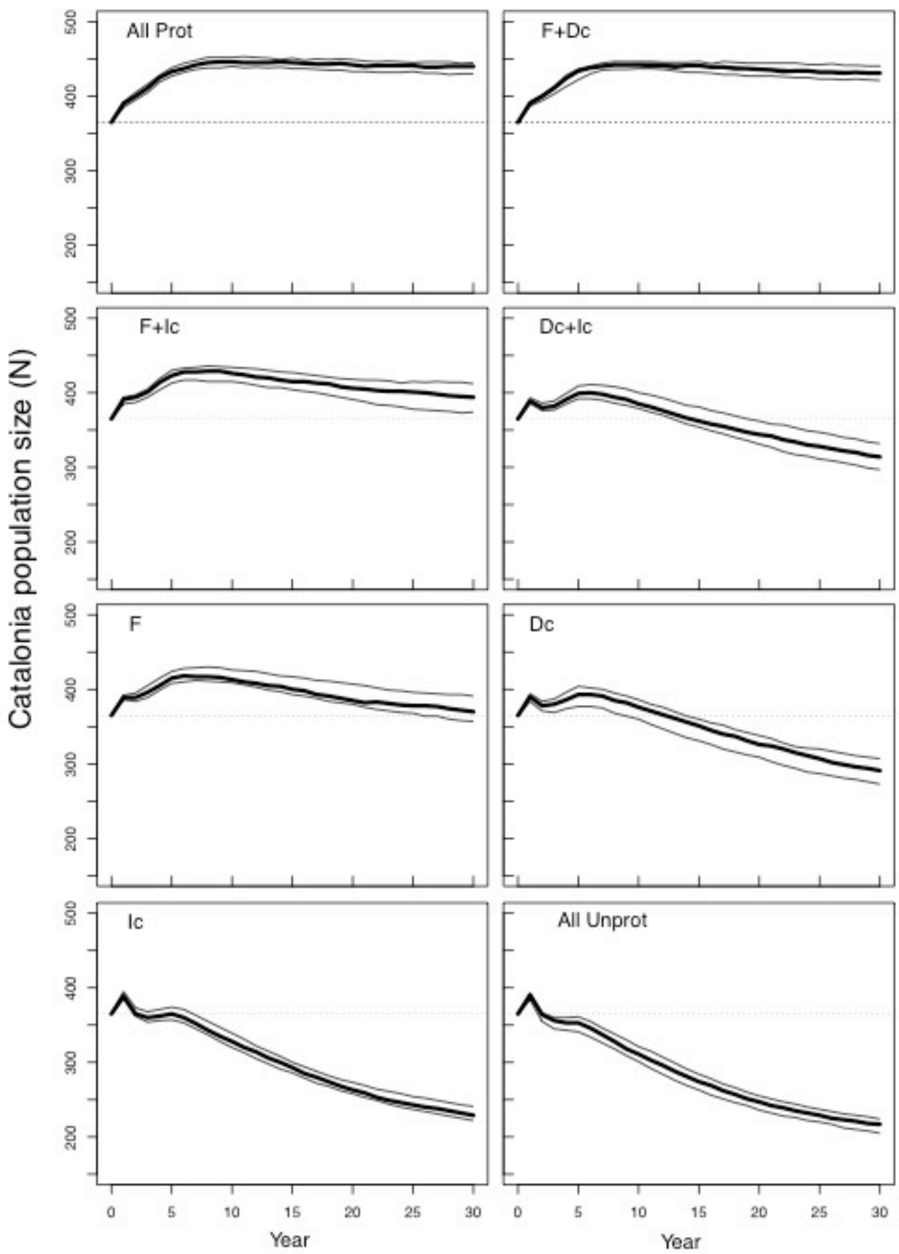

Figure S6. Sensitivity of Catalonian population trajectories for the following 30 years to variations of 5% increase (upper thin line) and 5% decrease (bottom thin line) in **fecundity** according to each conservation scenario. Thick solid line represents the average trajectory for Catalonia in each scenario; dotted lines represent the initial population size. All trajectories have different terminal extinction risk.

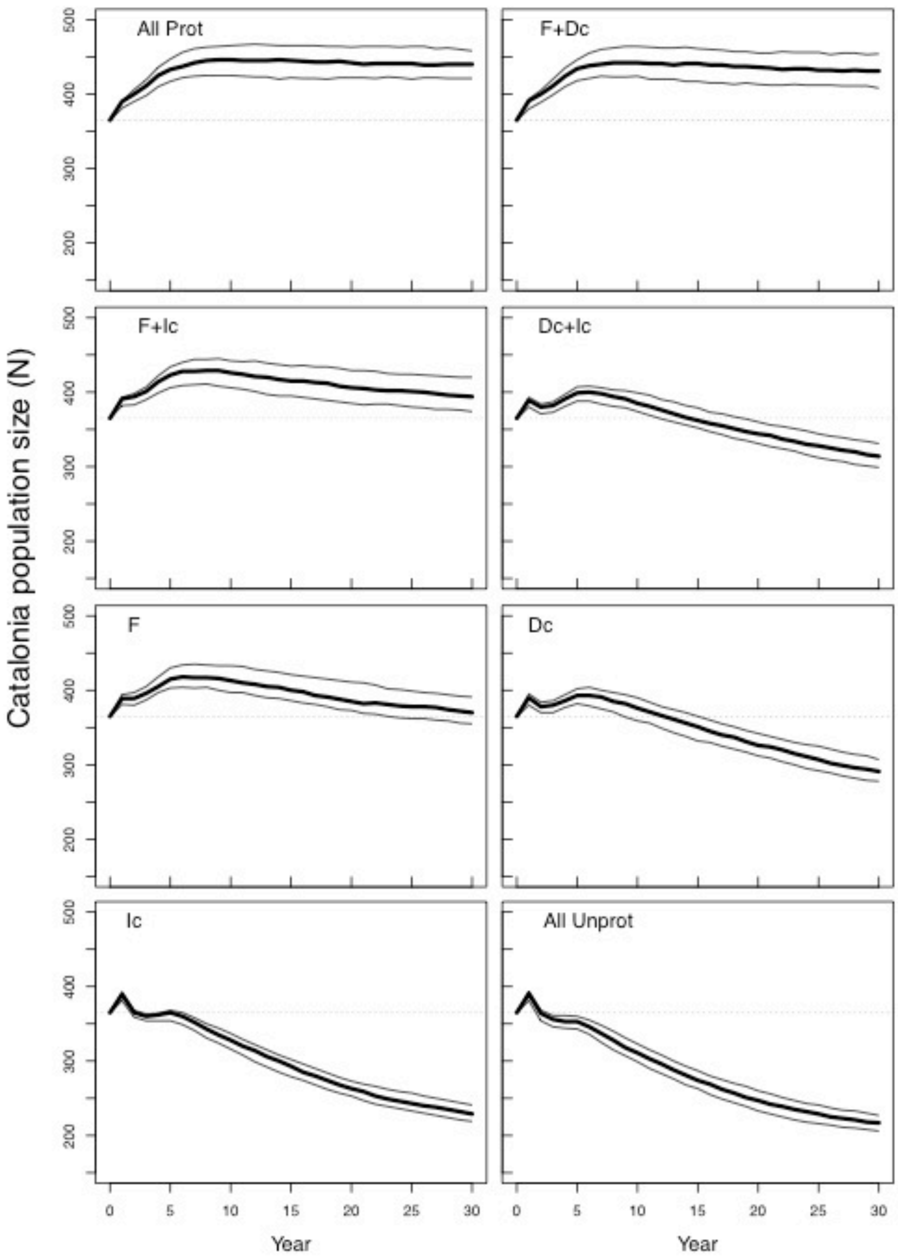

Figure S7. Sensitivity of Catalonian population trajectories for the following 30 years to variations of 5% increase (upper thin line) and 5% decrease (bottom thin line) in **carrying capacity** according to each conservation scenario. Thick solid lines denote the average trajectory of Catalonia in each scenario. Dotted lines represent the initial population size. All trajectories have similar extinction risk.

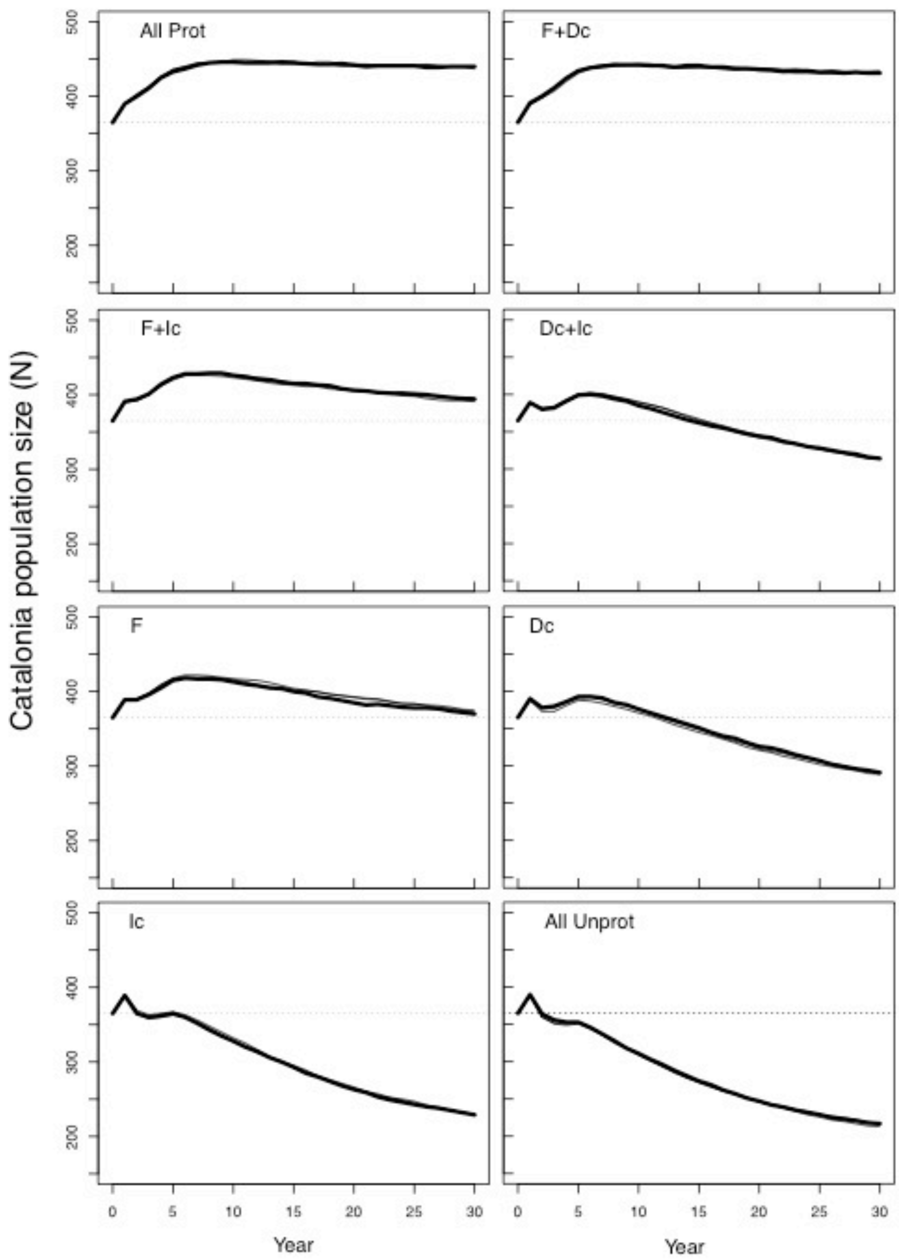

Figure S8. Sensitivity of Catalonian population trajectories for the following 30 years to variations of 5% and 10% increase in **dispersal** according to each conservation scenario. Thick solid lines denote the average trajectory of Catalonia in each scenario. Dotted lines represent the initial population size. None of the simulated trajectories have different terminal extinction risk.

Table S1. Terminal extinction risk differences of applying different management scenarios. Pairwise comparison between the extinction risk curves of each scenario according to Kolmogorov-Smirnov test. *D* represents the maximum vertical distance between the compared curves. Maximum vertical distance between the terminal extinction risk curves (*D*) of the eight basic scenarios. All comparisons are significantly different (p-value<0.001)

	All Prot (*D*)	*F+Dc* (*D*)	*F+Ic* (*D*)	*Dc+Ic* (*D*)	*F* (*D*)	*Dc* (*D*)	*Ic* (*D*)
F+Dc	0.08						
F+Ic	0.32	0.25					
Dc+Ic	0.69	0.64	0.45				
F	0.69	0.45	0.39	0.33			
Dc	0.78	0.74	0.55	0.15	0.46		
Ic	0.93	0.91	0.82	0.55	0.76	0.44	
All Unprot	0.96	0.94	0.88	0.64	0.83	0.54	0.12

Table S2. Terminal extinction risk differences of applying different rates of protection decrease. Pairwise comparison between the extinction risk curves of each scenario according to Kolmogorov-Smirnov test. *D* represents the maximum vertical distance between the compared terminal extinction risk curves. Comparisons are not significant (n.s) or significant (p-value * <0.05, **<0.001) terminal extinction risk.

Scenario	Rate	Instant (*D* p-value)	Fast (*D* p-value)	Moderate (*D* p-value)
All Unprot	Fast	0.06 n.s.		
	Moderate	0.15**	0.11***	
	Slow	0.34**	0.3**	0.25**
Dc	Fast	0.03 n.s.		
	Moderate	0.06*	0.05 n.s.	
	Slow	0.2**	0.19**	0.15**
Ic	Fast	0.1 n.s.		
	Moderate	0.15**	0.06 n.s.	
	Slow	0.25**	0.18**	0.14**
Dc+Ic	Fast	0.04 n.s.		
	Moderate	0.07*	0.04 n.s.	
	Slow	0.19**	0.15**	0.17**

Table S3. Sensitivity analyses of ±5% and ±10% changes in survival, fecundity, carrying capacity and dispersal initial parameters for all scenarios. As all scenarios (*All Prot, F+Dc, Dc+Ic, F, Dc, Ic, All Unprot*) respond similarly to changes in its parameters, therefore only one table is presented which summarizes the significance of these changes. Different letters show significant pair-wise differences (p<0.001) in the terminal extinction risk according to Kolmogorov-Smirnov test with respect to the initial scenario. The column named as scenario depicts the base-line average population trend result of each scenario as presented in the main manuscript body (Figure 2-I, II). For a graphical representation see figures S2-5.

Parameter	Scenario	±5%	±10%
Adult survival	a	b	c
Subadult survival	a	b	c
Juvenile survival	a	b	c
Fecundity	a	b	c
Dispersal	a	a	a
Carrying capacity	a	b	c